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Learning to Control Opening and Closing a Myoelectric Hand

Hanneke Bouwsema, MSc, Corry K. van der Sluis, MD, PhD, Raoul M. Bongers, MSc, PhD

ABSTRACT. Bouwsema H, van der Sluis CK, Bongers RM. Learning to control opening and closing a myoelectric hand. *Arch Phys Med Rehabil* 2010;91:1442-6.

Objective: To compare 3 different types of myoelectric signal training.

Design: A cohort analytic study.

Setting: University laboratory.

Participants: Able-bodied right-handed participants (N=34) randomly assigned to 1 of 3 groups.

Interventions: Participants trained hand opening and closing on 3 consecutive days. One group trained with a virtual myoelectric hand presented on a computer screen, 1 group trained with an isolated prosthetic hand, and 1 group trained with a prosthetic simulator. One half of the participants trained with their dominant side, and the other half trained with their nondominant side. Before and after the training period, a test was administered to determine the improvement in skill. Participants were asked to open and close the hand on 3 different velocities at command.

Main Outcome Measures: Peak velocity, mean velocity, and number of peaks in the myoelectric signal of hand opening and closing.

Results: No differences were found for the different types of training; all participants learned to control the myoelectric hand. However, differences in learning abilities were revealed. After learning, a subgroup of the participants could produce clearly distinct myoelectric signals, which resulted in the ability to open and close the hand at 3 different speeds, whereas others could not produce distinct myoelectric signals.

Conclusions: Acquired control of a myoelectric hand is irrespective of the type of training. Prosthetic users may differ in learning capacity; this should be taken into account when choosing the appropriate type of control for each patient.

Key Words: Artificial limbs; Electromyography; Learning; Rehabilitation.

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AFTER UPPER-LIMB AMPUTATION, myoelectrically controlled prostheses are often provided.¹⁻⁴ These prosthetic devices are controlled by a myoelectric signal produced by muscle activity, which controls an electric motor to open and close the prosthetic hand. Producing an appropriate myoelectric signal is imperative to a good control of the prosthetic

hand and is, therefore, a prerequisite for the functional use of the prosthesis in daily life.⁵

Appropriate myoelectric control is becoming more and more important given the recent technologic developments of prosthetic hands such as proportional control for opening and closing the hand at different speeds, and the control of multiple functions, for instance, hand opening and wrist rotation, with the myoelectric signal of 1 muscle site. This means that users have to learn to produce a specific myoelectric signal to control each function of the prosthetic hand.

Importantly, thus far, the part of the training focusing on the control of the myoelectric signal has been neglected in the research into prosthetic training.⁶⁻¹⁰ Up to now, it has not been examined whether training the control of myoelectric signals after the fitting of the prosthesis leads to comparable results as training in the preprosthetic phase (ie, from the amputation until fitting of the prosthesis) with a tabletop prosthetic hand or with a virtual prosthetic hand on a computer screen; the latter is becoming more and more available nowadays. Such information is necessary to decide whether novice amputees can start to train myoelectric control early (in the preprosthetic phase) instead of requiring a fitting first.

The aim of our study was to determine which of the following 3 training methods currently used in rehabilitation^{11,12} exhibits the strongest learning effect on controlling the myoelectric signal: training with a virtual prosthetic hand, training with a tabletop prosthetic hand, and training with a fitted prosthesis. Training with a virtual prosthetic hand and a tabletop prosthetic hand are both applicable in the preprosthetic phase.

METHODS

Participants

Thirty-four able-bodied right-handed participants were studied: 9 men (mean age, 21.10y) and 25 women (mean age, 20.04y). Inclusion criteria were as follows: (1) free of any neurologic or motor problems, (2) normal or corrected to normal sight, (3) right-handed, and (4) no earlier experience with a prosthetic simulator. The study was approved by the local ethics committee, and informed consent was given before participation. After completion of the experiment, participants received a gift voucher.

Materials

To train myoelectric control with a virtual hand, PAULA^a software was used in conjunction with a 757M11 MyoBoy^a with active socket electrodes (13E200 MyoBock Electrodes^a with a rectified and filtered [2nd-order] output, and linear sensitivity

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List of Abbreviations

ANOVA	analysis of variance
EMG	electromyogram
LED	light-emitting diode
PAULA	Prosthetists' Assistant for Upper Limb Architecture

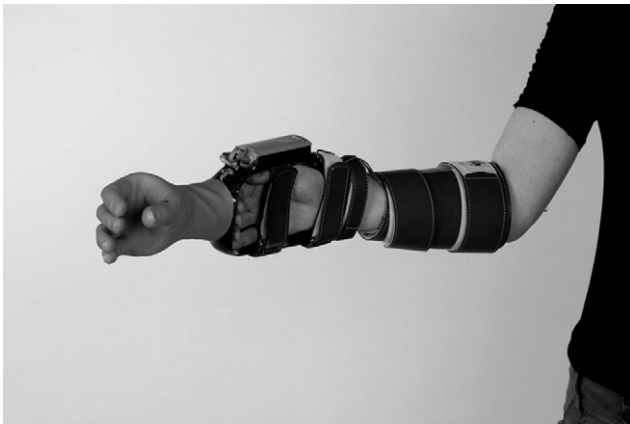


Fig 1. The myoelectric simulator.

controller) connected to a personal computer. PAULA software can be used to evaluate myoelectric control by means of feedback presented on the computer screen in the form of electromyographic signals or a virtual prosthetic hand. In this study, the virtual Sensor Hand Speed^a was used. The electromyographic signals were registered by a 32-channel PORTI recording system.^b

A myoelectric simulator¹³ was developed to resemble as closely as possible a myoelectric upper-extremity prosthesis for a below-elbow amputation (fig 1). The simulator consisted of the myoelectric hand attached to an open cast to place the hand and an in-length adjustable splint to attach the simulator to the forearm with a self-adhesive (Velcro) sleeve. The myoelectric hand attached was the MyoHand VariPlus Speed^a with proportional speed control (15–300mm/s) and proportional grip force control (0–approximately 100N). This type of hand was also used in the tabletop training condition. For this study, the MyoHand VariPlus Speed of the simulator and the tabletop hand were programmed to act like a Sensor Hand Speed, thus creating identical features and functions of the hands in all 3 experimental groups.

To measure the speed and range of opening and closing of the hand, the OPTOTRAK 3020 System^c was used, which records from above the table. Two infrared LEDs were sampled with a frequency of 100Hz. One LED was placed on the ulnar border of the thumbnail and the other one along the radial border of the nail of the index finger.

Design

Participants were randomly assigned to 1 of 3 training groups. The first group (V) trained with the virtual hand, the second group trained with a tabletop hand (T), and the third group trained with the simulator (S). Because amputations occur on both sides, one half of the participants trained with their dominant side, and the other half trained with their non-dominant side. The experiment was conducted in 3 days. On the first day, a pretest was conducted after which control of the hand was trained on 3 consecutive days. Groups V and T trained hand opening and closing 60 times in each of the sessions. Group S trained a functional task in which an object had to be grasped 30 times; each grasp and release of the object and returning to the start position represented 2 hand openings and closings, equaling the 60 times of the other training groups. After the last training session on the 3rd day, a posttest was administered to determine the level of skill after the training.

Procedure

Fitting of the electrodes. Participants were fitted with the electrodes with the help of the PAULA software. The exact positions of the electrodes were determined after palpation of the most prominent contraction of the muscle bellies of the extensors and flexors of the wrist. The sensitivity of the electrodes was adjusted to the upper threshold, a high level of myoelectric signal, for each participant individually. This fitting procedure had to be repeated each day before training could start to prevent environmental influences, such as perspiration of the skin, from influencing the myoelectric signals that were picked up by the electrodes. To prevent early learning as much as possible, a maximum of 10 contractions was allowed. The locations of the electrodes were marked so that the electrodes could be placed at the same position every experimental day. The speed of the hand was set to its maximum.

Pretest and Posttest

This study focused only on the myoelectric control of the prosthetic hand. Therefore, we could not use currently available assessments of prosthetic function like Southampton Hand Assessment Procedure,¹⁴ Assessment of Capacity for Myoelectric Control,² or University of New Brunswick Test of Prosthetic Function¹⁵ because all these tests assess the fitted prosthesis in a functional way. Moreover, a lot of these tests are observational or questionnaires. To assess the myoelectric control of the prosthetic hand, an objective, dynamic measure of performance was needed. Therefore, we designed a test consisting of 2 parts: the participant was asked to first provide a maximum myoelectric signal for at least 2 seconds (this was repeated 5 times) and, second, to open and close the hand to the maximal aperture on 3 different velocities at command. Participants were asked to control hand opening and closing at the slowest speed possible, at a comfortable speed, and at the highest speed possible. All velocities were executed 3 times in a random order. When the hand was not fully opened or closed, the participants were corrected and instructed again. This test was assessed as the pretest and the posttest. The tabletop prosthetic hand was used to register kinematic aspects of the myoelectric control and to eliminate interference with an attached prosthesis.

Training Sessions

During the training sessions, participants were instructed to fully open the hand, an aperture of approximately 10cm between the index finger and the thumb, and fully close the hand. Moreover, they were instructed to “play” with the proportional speed option of the hand. After every 20 times opening and closing the hand, participants were given a short break to prevent muscle fatigue. The participants who trained with the simulator had to grasp a wooden cylinder (10cm in height, 6cm in diameter) placed 30cm away from the start position of the hand. The start position of the hand was located 15cm from the edge of the table in line with the shoulder. The participants were instructed to grasp the cylinder, lift it approximately 5cm, place it back on the same position, and return it to the start position with the index finger and thumb touching each other. They had to perform the movements as rapidly and as accurately as possible. They were given a short break after every 10 grasps to prevent muscle fatigue.

Data Analysis

Custom-made programs were written in Matlab^d to compute the dependent variable from the raw position and EMG data. High-frequency noise was removed from the position data of

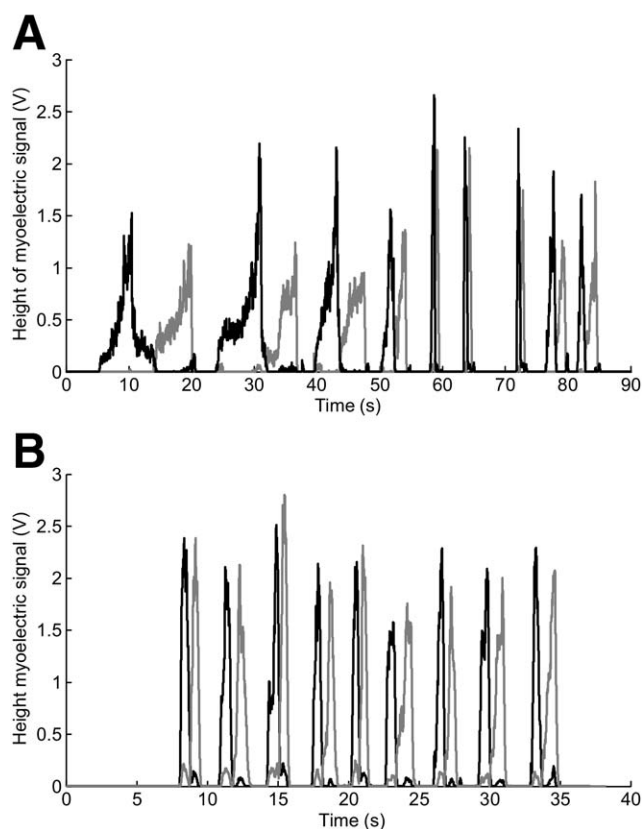


Fig 2. Illustrative examples of myoelectric signals of 2 different participants on the posttest. (A) The 3 different velocity conditions can be clearly seen in the myoelectric signals. The slow conditions are characterized by a wide myoelectric signal, whereas the fast conditions show a very narrow but high myoelectric signal. (B) The velocity conditions are difficult to distinguish. Note the different time scales of the 2 figures.

the OPTOTRAK LEDs using a 2nd-order recursive Butterworth filter with a cutoff frequency of 15Hz. The difference between the position of the markers on thumb and index finger of the tabletop hand defined hand opening. Hand opening was differentiated with a 3-point algorithm to acquire opening velocity. Kinematic measures of the opening reflect the control of the prosthetic hand. Peak velocity of the hand opening, peak velocity of the hand closing, and mean velocity over hand opening and hand closing were determined. We rejected trials in which the maximum hand opening was smaller than 95mm.

The local peaks (maxima) in the myoelectric signal were detected. A point was considered a peak if it had a maximum value and was preceded and followed by a value that was more than $7000\mu\text{V}$ smaller. The number of peaks was used to measure the smoothness. The amplitude of the myoelectric signal could not be used because the gain of the electrodes was adjusted to the same level, affecting the maximum myoelectric signal, for each participant every day.

A repeated-measure ANOVA was conducted on the peak velocity, the mean velocity, and the number of peaks in the EMG of hand opening and hand closing, with test (pretest and posttest), velocity condition (slow, comfortable, fast), and direction (opening and closing of the hand) as within-subject factors and training group (V, T, S) and dominance (dominant side and nondominant side) as between-subject factors. When sphericity was violated, the degrees of freedom were adjusted

with the Greenhouse-Geisser correction. In all analyses, a significance criterion of $\alpha \leq .05$ was used, and post hoc tests on main effects used Bonferroni corrections. Generalized eta squared^{16,17} was used to calculate effect sizes, and interpreted according to Cohen's recommendation¹⁸ of .02 for a small effect, .13 for a medium effect, and .26 for a large effect. Only the effects with an effect size larger than .02 are presented in the results.

RESULTS

The key question of our study was which of the 3 training methods had the largest learning effect on myoelectric control. Our results showed that the training groups did not differ in their capacity of myoelectric control (mean peak velocity [95% confidence interval]: V=450.31 [413.35–487.26]; T=468.23 [423.4–512.98]; S=418.56 [379.60–457.51]). Before we present the full analyses showing this, we first show characteristics of the myoelectric signal that led us to include an additional factor in the analyses. The myoelectric signals produced by each of the participants showed many individual differences in the posttest; some participants showed clearly distinct myoelectric signals for the different hand opening and closing velocities, whereas for other participants the signals were almost equal (fig 2).

Because of these apparent differences, we looked further into performance. We calculated the regression lines of the peak velocities in the posttest over the slow, comfortable, and fast velocity conditions for each individual participant. A high slope of the regression line indicates a high relation between the demanded and the performed velocity. Based on the average of the slope of the regression lines (.81), we split the participants into 2 different learning categories. Participants with a higher slope were classified as high-capacity learners, and participants with a lower slope were classified as low-capacity learners (fig 3). No systematic tendency could be observed in the distribution of the type of learning across the training groups ($\chi^2_2=2.24$, $P=.33$) and across arm dominance

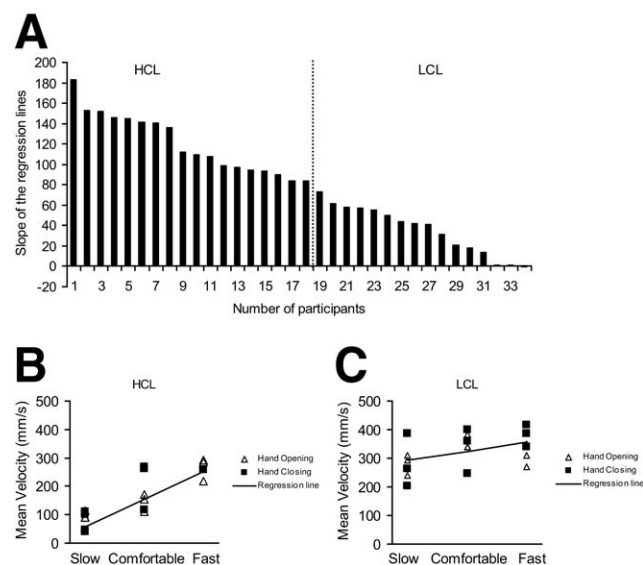


Fig 3. (A) Categorization of participants in high-capacity learners (HCL) and low-capacity learners (LCL), with the division based on the mean slope of the regression lines (.81). (B and C) The regression lines of the (B) same HCL participant and (C) LCL participant as shown in Figure 2.

Table 1: Overview of Significant Effects

Dependent Variable	Main Effect or Interaction Effect	F	P	η^2_G
Peak velocity (mm/s)	Velocity	82.02	.00	.28
	Learning type	18.87	.00	.12
	Test	54.54	.00	.08
	Arm	9.77	.00	.06
	Velocity by learning type	18.23	.00	.09
	Test by velocity by learning type	7.05	.01	.03
Mean velocity (mm/s)	Velocity	68.88	.00	.28
	Learning type	9.39	.01	.12
	Test	30.92	.00	.05
	Arm	19.84	.00	.06
	Direction	19.80	.00	.03
	Velocity by learning type	7.86	.01	.05
	Test by velocity	7.37	.01	.03
	Velocity by direction	11.47	.00	.02
Number of peaks	Velocity	44.93	.00	.32
	Learning type	15.32	.00	.09
	Test	36.94	.00	.02
	Group	6.02	.01	.07
	Velocity by learning type	10.64	.00	.11

($\chi^2_2 = .79$, $P = .67$). Therefore, statistical differences between groups cannot be attributed to differences in learning capacities of the participants of each group. The type of learning (high-capacity learners and low-capacity learners) was added to the ANOVAs, presented in the following, as a between-subject factor.

Peak Velocity and Mean Velocity

Both peak velocity and mean velocity showed the same main effects. Importantly, no significant differences were found between the 3 training groups for both dependent variables. A large effect was found for both peak velocity and mean velocity on the 3 velocity conditions (table 1); in the fast condition, the participants reached the highest velocities, whereas in the slow condition the velocities were lowest. Moreover, a moderate effect was found on the type of learning; high-capacity learners reached lower velocities compared with low-capacity learners. During the posttest, participants reached somewhat higher velocities than in the pretest.

A small to moderate interaction effect of velocity and learning revealed that although both learning types reached almost equal velocities in the fast condition, the high-capacity learners could reach much lower velocities in the slow condition compared with the low-capacity learners. The effect sizes of the other significant effects in table 1 are rather small and will not be discussed further.

Amount of Peaks

Analysis of the number of peaks in the EMG revealed the same effects as reported on the peak velocity and the mean velocity. A large effect of the velocity conditions showed that in the slow condition the most peaks occurred, whereas in the fast condition the fewest number of peaks were shown. The number of peaks in the posttest was somewhat less than in the pretest. The learning type showed a small to moderate effect; the high-capacity learners showed more peaks in the EMG than the low-capacity learners. The moderate interaction between velocity condition and learning type revealed that although the number of peaks was rather equal in the fast condition for both

learning types, the high-capacity learners showed more peaks in the slow condition compared with the low-capacity learners. A small effect of training group was found, which was different from the peak velocity and the mean velocity. This effect was mainly caused by 2 participants in the simulator group who had many more peaks in the slow condition relative to the other participants. Rerunning the ANOVA with the exclusion of these 2 participants revealed no effect of training group ($F_{2,18} = 1.96$, $P = .17$); rerunning the ANOVA 4 times with the exclusion of 2 randomly chosen participants showed the significant effect again. This provides evidence that the small effect of training group is because of the performance of these 2 participants.

DISCUSSION

The purpose of this study was to determine the training method with the highest effect on control of the myoelectric signal. Importantly, no differences were found between the 3 types of training, suggesting that training the myoelectric signal with a virtual or tabletop hand leads to comparable control of the prosthetic hand as functional training with a fitted prosthesis. Training with a virtual or a tabletop prosthesis can be provided in the preprosthetic phase to train independent and correct activation of the stump musculature for basic myoelectric functions,¹² whereas functional training is only possible after fitting of the prosthesis in the prosthetic phase. Our findings validate the use of virtual and tabletop prosthesis training instead of requiring a fitted prosthesis to train control of the myoelectric signal.

Moreover, our findings imply that early in rehabilitation (ie, in the preprosthetic phase) the level of control of a patient can be determined. Skills learned during preprosthetic training are important for motivation and success with the prosthesis.¹² Given that the most recent prosthetic hands are also available as virtual hands, the early start of training might speed up the complete rehabilitation process, including the selection of the most appropriate prosthetic components. This might be beneficial for prosthetists, patients, and insurance companies.

Importantly, at all phases of the experiment, all participants were able to generate a myoelectric signal that opened and closed the prosthetic hand. After training, higher velocities were reached in most conditions, which is probably because of more specific muscular control. This finding is in agreement with the study of Corcos et al¹⁹ who showed that after training over a single joint (in their study, it was the elbow) the peak velocities increased.

An interesting finding was that although all participants learned to open and close the hand, there were differences in the learning capacities; high-capacity learners could make a good distinction between the 3 different velocity conditions in the posttest, whereas low-capacity learners could not make this distinction. It seemed that the low-capacity learners had learned how to open and close the hand but could only contract their muscles in a single way, resulting in an almost invariable hand opening and closing velocity. They were not able to vary the myoelectric signal to fully use the available options of the proportional control of the prosthetic hand. Such a difference in learning abilities is also observed in rehabilitation practice. It is generally known that some patients can easily learn to use their prosthesis, whereas others are less proficient, suggesting that prosthetic users differ in learning capacity. If differences in learning capacity actually exist, it should be taken into account when choosing the appropriate control type for each individual patient. A patient who is skillful in myoelectric control would benefit more from a proportional control type, whereas a patient with less proficient myoelectric control might be better off

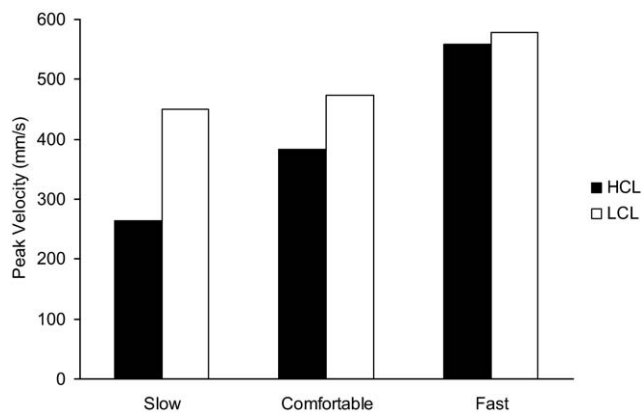


Fig 4. Peak velocity reached in the pretest and the posttest for the high capacity learners (HCL) and low capacity learners (LCL) plotted for each of the velocity conditions.

with an on-off switch control type. This suggests that patients should be fitted with the most appropriate control system, which might increase the chance of acceptance and use of the prosthesis. Moreover, it could be that at least a portion of the low-capacity learners might be able to learn proportional control too, but this might take longer than the 3 days of training used in this study. More research is needed to be able to make a better distinction between different types of learners.

Study Limitations

In this study, we used able-bodied participants instead of recently amputated patients. With able-bodied participants, we did not have to bother the very small group of patients who had just been amputated and could therefore test more subjects. A recent study performed by Schabowsky et al¹⁰ studying motor performance in amputees as well as able-bodied participants showed that the learning skills of the amputees were similar to the unimpaired participants. Although we expect to find similar results of our study in amputated patients, further research is needed to establish the generalization of our findings to the amputee population. Another limitation of the study is the fact that we divided the participants post hoc into different learning capacities. We did not expect to find differences in learning beforehand; however, this interesting finding was worth mentioning. In future experiments, it is recommended to define possible differences in learning ability in advance.

CONCLUSIONS

In conclusion, learned control of a myoelectric hand does not depend on the type of training (with a virtual hand, an isolated hand, or a prosthetic simulator). Prosthetic users may differ in learning capacity, and this should be taken into account when choosing the appropriate type of control for each patient. (fig 4).

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Suppliers

- PAULA software; 757M11 MyoBoy; 13E200 MyoBock Electrodes; Sensor Hand Speed; MyoHand VariPlus Speed; Otto Bock HealthCare Products Ges mbH, Kaiserstrasse 39, 1070, Vienna, Austria.
- PORTI Recording System; Twente Medical Systems, Zutphenstraat 57, 7575 EJ, Oldenzaal, The Netherlands.
- OPTOTRAK 3020 System; Northern Digital, 103 Randall Dr, Waterloo, Ontario, N2V 1C5 Canada.
- Matlab, The MathWorks, 3 Apple Dr, Natick, MA 01760-2098, USA.